NUREG-0208

DEVELOPMENT OF HIGH-SENSITIVITY ULTRASONIC TECHNIQUES FOR IN-SERVICE INSPECTION OF NUCLEAR REACTORS

Annual Report
July 1, 1975 - June 30, 1976

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National Bureau of Standards
for
U. S. Nuclear Regulatory Commission

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NUREG-0208
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DEVELOPMENT OF HIGH-SENSITIVITY ULTRASONIC TECHNIQUES FOR IN-SERVICE INSPECTION OF NUCLEAR REACTORS

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M. Linzer

Manuscript Completed: February 1977
Date Published: April 1977

Institute for Materials Research
National Bureau of Standards
Washington, D. C. 20234

Prepared for the U. S. Nuclear Regulatory Commission
Division of Reactor Safety Research
Under Contract No. B5680

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ABSTRACT

During the period covered by this report, substantial progress was made in the development of improved ultrasonic techniques based on real-time signal averaging, pulse compression, multifrequency transception, and compact electromagnetic transducers. A preliminary correlation was established between ultrasonic velocity and the degree of sensitization of stainless steel.

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INTRODUCTION

This report covers work performed during the first year (July 1, 1975 - June 30, 1976) of a three year program on the development of high-sensitivity ultrasonic techniques for nuclear reactor inspection. Because of other programmatic commitments, no work was performed and hence no funding provided by NRC for the period of July 1, 1976 to September 30, 1976. The program is expected to terminate on September 30, 1978.

During the period covered by this report, substantial progress was made in the development of improved ultrasonic techniques based on real-time signal averaging, pulse compression, multifrequency tranception, and compact electromagnetic transducers. A preliminary correlation was established between ultrasonic velocity and the degree of sensitization of stainless steel.

II. PROGRAM OBJECTIVES

The principal objective of this program is to develop techniques to enhance the sensitivity of ultrasonic signals which are below the random noise of the system. Such techniques can be used to locate minute flaws, presently undetectable, which might grow to larger size during service; to remotely inspect regions which have limited access, either because of the physical constraints of the reactor design or because of radiation hazards, and to locate flaws which are embedded within or accessed through highly-attenuating material such as coarse-grained austentic steel. A secondary objective is to develop instrumentation for improved discrimination of flaw signals from background "clutter" and for characterization of failure-related material properties through measurements of ultrasonic parameters such as velocity and attenuation.

III. RESULTS

A. Sensitivity Enhancement Techniques

Improved discrimination against random noise may be achieved by decreasing the noise figure of the receiver, increasing transducer efficiency, decreasing system noise bandwidth, and increasing power input to the material. High-quality commercial ultrasonic receivers have noise figures close to the state-of-the-art and very little improvement can be expected in this direction. Maximum conversion efficiency of ultrasonic transducers may be obtained by using the most sensitive transducer material currently available, *i.e.*, PZT-5, and matching its acoustic impedance to that of the material being studied and its electrical impedance to that of the electronic circuit. Decreased noise bandwidth may be accomplished by means of signal averaging techniques; this approach, however, may also be regarded as a means of increasing power input to the system. Further increases in power input and hence sensitivity may be achieved by use of higher-power transmitters, transducer arrays, focusing, and pulse compression techniques.

Efforts in the past year have concentrated on developing techniques based on signal averaging and pulse compression. Other elements which contribute to improved sensitivity, such as high-power insonification, dynamic focusing, and transducer matching, will be incorporated in the coming year.

1. Signal Averaging

Digital signal averaging is accomplished by repetitive pulsing, digitizing the echo signals, and adding the results of all the scans in a coherent fashion. An ideal averager integrating over N scans will improve the sensitivity by a factor of $\sqrt{N}$ over single scan detection. Hence, at a pulse rate of 10 kHz and an observation time of 100 seconds, one can in principle obtain a sensitivity enhancement of 1000:1.

A high-speed real-time signal averaging system suitable for averaging ultrasonic signals has been under development at NBS for over three years, supported by the NBS program in nondestructive evaluation. In the past year, averaging of analog signals has been achieved at rates exceeding 25 MHz (Figure 1). An eight-fold multiplexing scheme is employed to obtain these extremely fast averaging rates. The device has a memory of 4K words by 24 bits, computer and CRT readout, and cursor-selected digital readout of the amplitude of individual points. Work is in progress to increase the sampling rate and to develop additional convenience features. The device is expected to be completed by January, 1977.

2. Pulse Compression

Pulse compression techniques are widely used in radar to overcome peak power limitations in the transmitter circuitry. These systems operate by transmitting a long RF burst with acceptable peak power, which, in reception, is compressed to a time interval short enough to give the desired range resolution. Since pulse compression techniques allow more power to be transmitted into the component, they can be used to increase the S/N ratio of the ultrasonic echoes.

In the past year, we have demonstrated the first practical pulse compression system applicable to ultrasonic NDE. A prototype device with 8:1 compression ratio and 0.6 μs bandwidth was developed and used to observe echo waveforms from an aluminum bar. A report of this work has been given in a recent paper.[1]

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2.1 Basic Principles of Pulse Compression

The most common waveform employed in pulse compression systems is the linear F.M. or "chirp" waveform. The ideal chirp pulse, shown schematically in Figure 2a, is an RF burst of constant envelope amplitude, with frequency varying between f_1 and f_2 in time T. This waveform may be compressed to that shown in Figure 2b by passing it through a dispersive delay line whose slope of frequency *vs.* time delay is equal and of opposite sign to that of the F.M. waveform. In practical systems, the compressed signal has a halfwidth of $1/|f_1-f_2| \equiv 1/B$, where B is the bandwidth of the dispersive filter. The original F.M. waveform has thus been compressed by a factor equal to BT.

A dispersive delay line, based on a surface acoustic wave interdigital transducer, is schematically illustrated in Figure 2c. The various frequency components of the F.M. waveform are launched on the piezoelectric substrate only by electrodes whose spacing is about one-half wavelength. The low frequency components thus travel a longer distance and undergo a longer delay than the high frequency components before reaching the broadband output element. Since the low frequency portion of the waveform is inserted first into the device, all the components appear simultaneously at the output to give a compressed pulse.

One of the undesirable results of this compression process is the appearance of time sidelobes on both sides of the compressed pulse. Since the F.M. burst has a rectangular envelope, the output waveform will resemble a (sin t)/t function, with first sidelobes only 13 dB down from the main lobe. These sidelobes may be reduced by suitable amplitude and phase weighting (apodization) at the expense of main lobe

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broadening. Sidelobe reductions of up to 40 dB may be achieved, with the main lobe broadened by up to 50%.

2.2 Experimental Techniques and Results

A block diagram of our system is shown in Figure 3. An F.M. burst of ultrasonic energy is transmitted by a broadband transducer (5.5 MHz center frequency, 5 MHz bandwidth), reflected off an interface, and received by the same transducer. Following frequency dependent time-gain compensation (TGC), the signal is translated to the operating frequency range of the chirp filter (30-34 MHz), and then compressed. The compressed pulse is then detected and displayed on the oscilloscope.

Figure 4 shows some experimental results obtained with our system. Waveforms A and B show the system performance in near ideal circumstances, a normal reflection from a smooth back surface of an aluminum bar. Note that a pulse compression of about 8:1 has been achieved.

The particular dispersive filter used in this work has a bandwidth and expanded pulse duration suitable for contact scanning of steel lying at least 3 cm below the surface. The use of longer pulse durations would either require a buffer to serve as a delay line between the transducer and component, or require a two transducer system. A two transducer device with longer pulse duration (420 µs) but poorer range resolution (8 µs) was recently reported.[2] However, its range resolution ($\sim$ 5 cm in steel) makes it impractical for flaw detection. Our filter also has a third harmonic mode with three times greater bandwidth and compression ratio than the fundamental mode. Development of this system and other pulse compression devices with higher compression ratios is currently underway.

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3. Other High-Sensitivity Techniques

We are planning to construct a high power insonification system in FY 77. The maximum power which will be employed will be dictated by the power handling capacity of the transducer elements. Another area to be explored is power concentration in the material by the use of an electronically-focused concentric annular array. This approach would also have the additional advantage of improving lateral resolution. Finally, sensitivity enhancement by use of acoustic matching elements between the transducer and material will be investigated. Insertion losses as low as 6 dB have been reported for impedance matching by means of 1/4 wave plates. Impedance matching also results in broadening the frequency response of the transducer, thus yielding increased spatial resolution and increased range for spectral analysis.

4. Electromagnetic Transducers

Electromagnetic transducers have many characteristics which make them desirable for nuclear reactor monitoring. Because they are contactless, electromagnetic transducers lend themselves to automated and reproducible scanning and are suitable for monitoring components in motion or at high temperatures. Their principal problem is lack of sensitivity (insertion loss of $\sim$ 60 dB relative to PZT). This drawback can be surmounted, however, by the use of our signal averaging/pulse compression system, since it would provide a sensitivity enhancement of 60 dB in several seconds of averaging. Another major problem has been the large size and weight of the magnets used to generate the high magnetic fields necessary for high sensitivity. Accordingly, we have developed compact and lightweight electromagnetic transducers incorporating very high field cobalt-samarium magnets. This work is fully described in a paper recently published[3] and in another paper now in press.[4]

B. Techniques for Background Discrimination and Measurement of Bulk Material Properties

1. Multifrequency Tranceiver System

In a recent paper in the Soviet Journal of Nondestructive Testing[5], considerable success was reported in discriminating against background by simultaneously transmitting and detecting at two or three ultrasonic frequencies. Scattering by dendritic structures within welds was found to constructively or destructively interfere, depending on the insonifying frequency, thereby leading to pronounced amplitude changes with frequency. Scattering from flaws, on the other hand, exhibited a smooth and gradual change of intensity with frequency and could thus be distinguished from microstructural scattering.

Because of the success of this work, it was decided to construct a multiple-frequency tranceiver system. An output at two arbitrary frequencies is generated by a digital double-sideband suppressed-carrier technique. Capability for generating two or more harmonically-related signals is also provided. After wideband amplification, the received signal is heterodyned to an IF frequency region and then sent to different filter/detectors to yield frequency-resolved information.

The system is now capable of yielding the amplitude ratio at two frequencies. A circuit for measuring the relative phase of two harmonically-related frequencies is under development. A paper describing this system will be submitted for publication in 1977.

2. Measurement of Bulk Material Properties

A study was made of the feasibility of ultrasonic measurements in detecting sensitization of type 304 stainless steel. A recent investigation into the cause of leaks in BWR recirculating bypass pipes has establsihed that most of these occurred in the heat-affected zones near the welds. Heating of these sections of pipes during the welding process sensitizes the material and makes it more susceptible to stress-corrosion cracking. This process occurs by intergranular precipitation of chromium carbides, which, although affecting only slightly the material's mechanical properties (there is some loss of ductility at subzero temperatures), severely reduces its resistance to stress-corrosion cracking.

A variety of stages of sensitization was examined on samples 7.6 cm long by 2.5 cm diameter of type 304 stainless steel rod. The ultrasonic sound velocity was determined at several frequencies using the pulse-echo overlap method. A significant increase in the sound velocity was observed with increasing degree of sensitization. Metallography revealed a corresponding increase in the rate of attack of the chemical etchant. Different thicknesses of rod are now being investigated in order to determine the minimum size sample in which such a velocity change could be detected. Ultrasonic velocity measurements are also being used to investigate sensitization in a welded sample of 6 mm thick type 304 stainless steel. Preliminary results indicate that full sensitization may be distinguished by these conventional (integrated) velocity measurements in thicknesses as small as 3 mm. This type of measurement, however, may be insufficient for field monitoring of stainless steel pipe welds, since only partial sensiti-

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zation can occur and the sensitization of interest is confined to the inside surface. A more sensitive ultrasonic velocity measurement, based on computerized ultrasonic tomography, should be capable of detecting such small perturbations. An experimental and theoretical study of the potential of this technique for NDE of materials has recently been published.[6]

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IV SUMMARY

Significant progress has been achieved in the past year in developing high sensitivity techniques for ultrasonic inspection of nuclear reactor components. Work has been carried out on high-frequency signal averaging, pulse compression, compact electromagnetic transducers, computer-assisted tomography, and detection of sensitization of stainless steel by ultrasonic velocity measurements. Papers have been published on pulse compression, electromagnetic transducers, and computer-assisted tomography, and additional papers are expected to be submitted in 1977 on signal averaging, multi-frequency transception, and the sensitization problem. Efforts in FY 77 will concentrate on the development of techniques for discrimination against random noise and on their application to nuclear reactor monitoring.

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V. REFERENCES

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A B

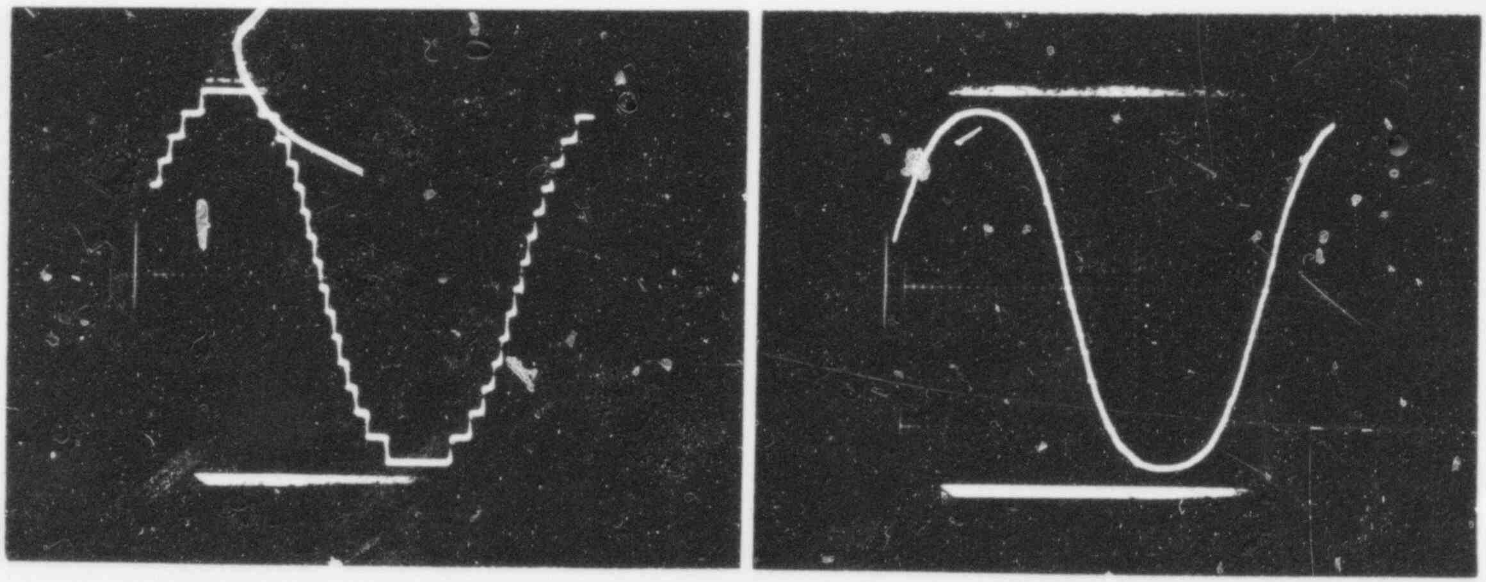

Figure 1. Demonstration of averaging capability of NBS system. Input sinusoid is quantized by 16-level analog-to-digital converter and averaged 256 times. Horizontal axis consists of 4,000 samples at 40 ns/sample. A) Signal without additive noise. B) Signal after noise equal to one-sixteenth of full scale is added. Averaging smoothes out the coarse quantization steps produced by the analog-to-digital converter.

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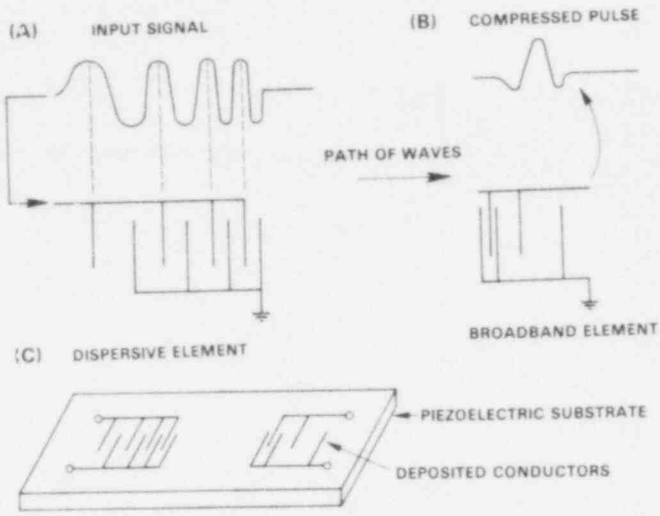

Figure 2. Simplified picture of the dispersive filter used to recompress "chirp"-encoded ultrasonic echoes. The filter has a delay *vs.* frequency characteristic complementary to the input chirp rate, so that low-frequency wavefronts "catch up" to high-frequency wavefronts to make a short composite pulse.

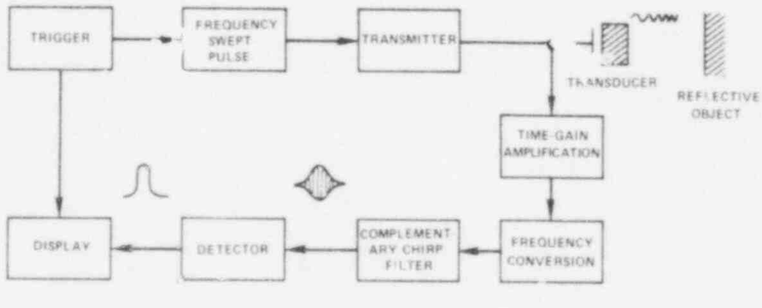

Figure 3. Block diagram of pulse compression ultrasound system.

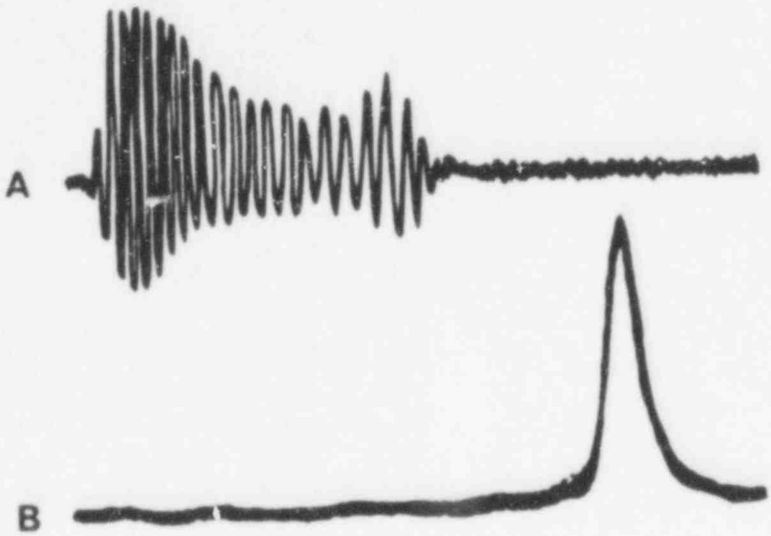

Figure 4. (A) Preamplified normal echo from the rear of an aluminum block. (B) The same signal following compression and detection. A 4.8 μs pulse is compressed to a halfwidth of 0.6 μs.

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